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Research on the application of polar-angle composite coding in laser protection for imaging systems

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Abstract: Wavefront coding technology redistributes optical energy to suppress local peak intensities and decodes captured images to recover background details, thereby providing effective laser protection without degrading imaging performance. This paper examines the physical origin of multiple zero crossing oscillations in the modulation transfer function (MTF) caused by vortex encoding, and proposes the use of a non-radially symmetric hollow point spread function (PSF) as a design guideline for encoding phases. Phase patterns designed under this guideline achieve effective laser suppression without compromising the system's ability to resolve fine details. Based on this guideline, this paper proposes a hybrid azimuthal encoding technique that combines vortex encoding with polar angle cubic encoding (VE-PACE). Compared with single vortex encoding, the proposed VE-PACE scheme not only achieves better laser suppression performance but also improves the MTF characteristics of the imaging system. When applied to a separated achromatic imaging system, the system MTF values can be maintained above 0.2 over the spatial frequency range below 100 lp/mm. The results of this study are expected to provide theoretical references and engineering guidance for the design of wavefront encoding in laser protection applications.

I. Introduction

With the rapid development of high-power laser technology, it has found wide applications in fields such as industrial processing, national defense security, and electro-optical countermeasures [1,2]. However, while high-energy lasers enhance system performance, they also pose serious challenges to the safety and stability of optical imaging systems [3]. The incidence of intense laser light can not only saturate detectors but also cause irreversible damage to sensitive optical components [4]. Therefore, how to effectively regulate the incident light energy while ensuring imaging quality has become an important issue that must be addressed in the design of modern electro-optical imaging systems [5]. Traditional laser protection methods mainly employ neutral density filters [6], mechanical blocking [7,8], or nonlinear optical materials [9]. Although these approaches can attenuate incident light intensity to a certain extent, they often simultaneously weaken the useful signal and even impair the imaging performance of the system [10]. In contrast, wavefront coding modulation, through careful design of the optical field phase, can redistribute energy spatially without significantly losing total energy, thereby effectively reducing local peak intensity [11]. Moreover, with respect to background information, wavefront coding can confine imaging degradation within a reversible range and restore image details through digital decoding and deconvolution [12]. This offers a new approach to laser protection.

Since Ruane et al. introduced wavefront coding technology into the field of laser protection in 2015 [13], significant progress has been made in this direction in terms of phase mask design and imaging performance optimization. In 2016, Watnik et al. verified the recovery capability of incoherent scenes under vortex and axicon masks [14]. During 2017–2018, Wirth et al. experimentally investigated the

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protection and imaging performance of various phase masks and proposed a low peak intensity point spread function, which reduced the peak intensity by two orders of magnitude [15,16]. In 2018, Wang et al. proposed an arcsine type phase mask, which outperformed the cubic phase plate in depth of field extension [17]. In 2019, the same group further proposed a laser blinding protection method based on light-field imaging, which reduced the maximum single pixel received power on the imaging plane by more than 78% and increased the blinding threshold by nearly an order of magnitude [18]. In 2023, Li et al. compared the protection performance of six phase masks through simulations, and the results showed that the cubic phase mask performed the best, achieving a reduction of approximately 95% in the maximum single pixel received power on the imaging plane [19]. In 2024, Lu and Li et al. proposed and modeled a spiral axicon phase mask, which redistributes the energy from an Airy disk into a hollow ring shaped structure, offering strong robustness and wide range propagation distance adaptability [20]. In 2025, Peng et al. proposed a computational imaging framework named NeuSee for realizing full-spectrum imaging and laser suppression [21]. In 2026, Zhou et al. discussed laser protection methods based on sinusoidal phase encoding, and their study showed that this encoding approach provides a good balance between preserving image details and achieving a high suppression ratio [22]. The above studies fully demonstrate that the wavefront-coded optoelectronic imaging system can effectively resist high-power laser blinding while maintaining good imaging quality. Previous work has pointed out that there is a trade-off between high laser suppression and preservation of more image details, and some encoding phases have been designed to address this issue; however, they have not clarified how to preserve more details while achieving a high laser suppression ratio, nor have they summarized the balancing rules that wavefront coding should follow. To this end, by investigating the physical mechanism of vortex coding that causes multiple zeros and oscillations in the modulation transfer function (MTF), this paper derives the rules that a wavefront coding system should follow to retain more image details under the premise of obtaining a high laser suppression ratio. On this basis, a hybrid coding method combining vortex encoding with polar-angle cubic encoding (VE-PACE) is proposed and applied to a separate achromatic imaging lens. Finally, by evaluating the MTF of the hybrid coding system, it is verified that this method can effectively suppress the damage of high-energy lasers to the imaging system while maintaining satisfactory imaging performance, further confirming that the coding rules summarized in this paper can provide guidance for the design of wavefront coding imaging systems.

II. Physical Mechanism of MTF Zero-Crossing Oscillations in Imaging Systems

In contrast to ordinary incoherent light, laser radiation is characterized by high brightness and excellent directionality. In conventional imaging systems, the incident laser beam is concentrated onto the detector plane, resulting in a localized high energy density. Should this energy density surpass the detector's damage threshold, detector failure will ensue directly. To prevent detector damage, wavefront coding can be applied to the incident beam at the pupil plane of the imaging optical system, so that the laser beam cannot be focused to a point, thereby reducing the energy density on the detector surface. It is well known that applying vortex phase modulation (*i.e.*, vortex encoding) to a Gaussian laser beam can transform it into an annular hollow beam. Therefore, when vortex encoding is introduced into an imaging system, the point spread function (PSF) of the system takes the form of a hollow annular spot, which effectively reduces the local optical power. Taking the simple single-lens imaging system shown in Fig. 1 as an example, the pupil plane is located at and in close contact with the front surface of the lens. Performing vortex encoding at the pupil plane, *i.e.*, setting the wavefront phase on the pupil plane to $\exp(il\theta)$, causes the PSF of the imaging system to become a hollow annular spot, as shown in Fig. 1. Here, l is the topological charge of the vortex phase. Obviously, as the topological charge l increases, the

PSF distribution of the imaging system becomes more spread out.

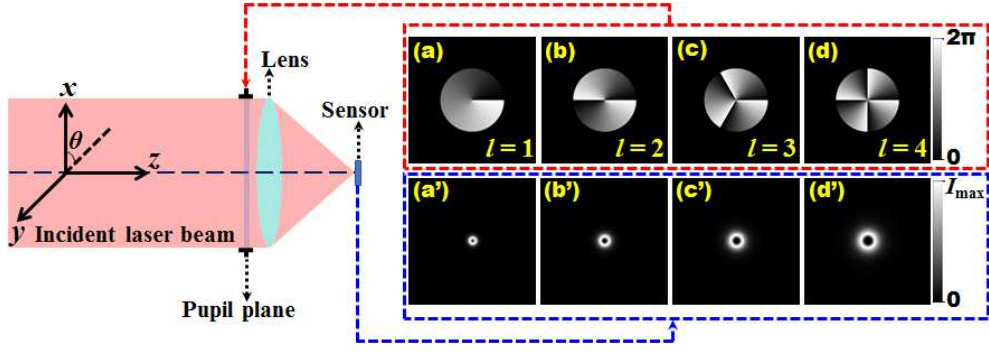


FIG. 1 Imaging schematic of a laser beam entering an vortex coding optical system. (a) – (d) denote the wavefront coding phases, while (a') – (d') denote the corresponding PSF on the image plane of the detector.

To quantitatively evaluate the suppression effect of this wavefront coding on laser energy density, we introduce the laser suppression ratio (LSR), which is defined as the ratio of the peak irradiance at the image plane with coding phase to that without coding phase, as given by Eq. (1). A smaller LSR value indicates a more significant suppression of the peak power at the image plane by wavefront coding.

$$\text{LSR} = \frac{I_{\text{Peak-irradiance(coded)}}}{I_{\text{Peak-irradiance(uncoded)}}} \quad (1)$$

Owing to the radial symmetry of the PSF under vortex encoding, we adopt only the one-dimensional distribution curves of the PSF for comparison of the LSRs at different topological charges. As depicted in Fig. 2 (a), the LSR gradually decreases with increasing topological charge; when the topological charge equals 4, the suppression ratio reaches 0.032, which means that vortex encoding can reduce the peak power of the incident laser beam on the pixel target plane to approximately 1/33 of its original value (*i.e.*, by a factor of about 33). Obviously, vortex encoding transforms the solid intensity distribution of the Airy disk into a hollow annular distribution, thereby effectively suppressing the damage to the imaging system caused by excessive saturation intensity on the image plane. However, further calculation of the system MTF (results shown in Fig. 2(b)) reveals that while vortex encoding suppresses the saturated light intensity, it also significantly compresses the distribution range of MTF in the spatial frequency domain. Moreover, as the topological charge l increases, the effective frequency width of MTF gradually narrows, implying that the imaging system will lose more image details during imaging. In addition, vortex encoding induces an oscillatory distribution of MTF in the spatial frequency domain with multiple zero-crossing points, and the number of these zeros increases with the topological charge. MTF quantitatively describes the transfer efficiency of an imaging system for signals at different spatial frequencies. A zero MTF value signifies the loss of image information during imaging, and this loss cannot be recovered by decoding algorithms. To avoid irreversible information loss caused by MTF zeros, and to enable the targeted design of wavefront coding schemes that can both effectively protect against laser damage and ensure good imaging performance, it is necessary for us to investigate the underlying causes of the multiple zero-crossing oscillations in MTF induced by vortex encoding.

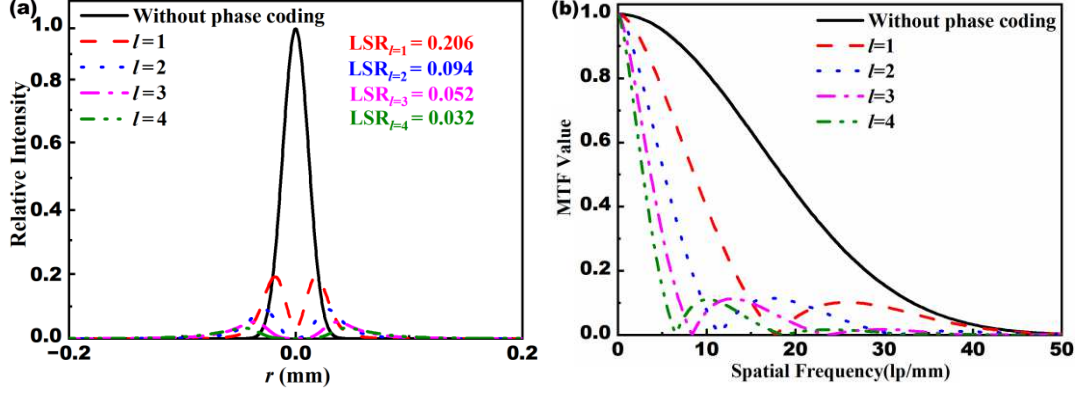


FIG. 2 PSF and MTF distribution curves of a single-lens imaging system under vortex encoding with different topological charges. (a) PSF distributions; (b) System MTF as a function of spatial frequency.

Mathematically, the MTF of an imaging optical system equals the modulus of the Optical Transfer Function (OTF), and the OTF can be derived from the autocorrelation of the generalized pupil function, which can be expressed as

$$f(r, \theta) = p(r, \theta) \exp(iW(r, \theta)). \quad (2)$$

Let $W(r, \theta)$ be the wavefront coding function in the polar coordinate system of the imaging system, and the vortex coding function is

$$W(r, \theta) = \exp(il\theta). \quad (3)$$

The pupil function takes the value 1 inside the pupil and 0 outside, and can be expressed as

$$p(r, \theta) = p(r) = \begin{cases} 1 & r \leq R \\ 0 & r > R \end{cases} = \text{circ}\left(\frac{r}{R}\right). \quad (4)$$

According to the Wiener-Khinchin theorem, the autocorrelation function is equal to the inverse Fourier transform of the power spectrum. Therefore, in order to calculate the autocorrelation of the vortex-encoded imaging system, a Fourier transform is first applied to the generalized pupil function, yielding the optical field distribution on the image plane of the vortex coded imaging system, as given in Eq. (5).

$$\begin{aligned} F(\rho, \varphi) &= \int_0^\infty \int_0^{2\pi} p(r, \theta) \exp(iW(r, \theta)) \exp(-ir\rho \cos(\varphi - \theta)) r dr d\theta \\ &= \int_0^\infty \int_0^{2\pi} \text{circ}\left(\frac{r}{R}\right) \exp(iW(r, \theta)) \exp(-ir\rho \cos(\varphi - \theta)) r dr d\theta \\ &= \int_0^R \int_0^{2\pi} \exp(iW(r, \theta)) \exp(-ir\rho \cos(\varphi - \theta)) r dr d\theta \end{aligned} \quad (5)$$

Further substituting Eq. (3) into Eq. (5) yields the optical field distribution on the image plane of the vortex-encoded imaging system as

$$F(\rho, \varphi) = \int_0^R \int_0^{2\pi} \exp(il\theta) \exp(-ir\rho \cos(\varphi - \theta)) r dr d\theta. \quad (6)$$

After performing the integration,

$$F(\rho, \varphi) = i^l \frac{R}{\rho} \exp(il\varphi) J_{l+1}(2\pi R\rho) \quad (7)$$

is obtained. Where ρ is the radial coordinate in the polar coordinate system of the image plane, φ is the angular coordinate, and J_{l+1} is the Bessel function of the first kind of order $l+1$. The intensity distribution on the image plane is precisely the power spectrum, given by

$$|F(\rho, \varphi)|^2 = |F(\rho)|^2 = \left(\frac{R}{\rho}\right)^2 J_{l+1}^2(2\pi R\rho). \quad (8)$$

As shown in Eq. (8), under vortex encoding, the spatial distribution of the power spectrum is independent of the polar angle φ , *i.e.*, it possesses radial symmetry; therefore, its inverse Fourier transform is equivalent to the inverse zero-order Hankel transform. Furthermore, the autocorrelation operation of the generalized pupil function with vortex coding is also equivalent to the inverse zero-order Hankel transform of the power spectrum, *i.e.*,

$$\begin{aligned} \text{OTF}(u) &= 2\pi \int_0^\infty |F(\rho)|^2 J_0(2\pi u\rho) \rho d\rho \\ &= 2\pi R^2 \int_0^\infty \frac{J_{l+1}^2(2\pi R\rho)}{\rho} J_0(2\pi u\rho) d\rho, \end{aligned} \quad (9)$$

where u is the radial spatial frequency. It is evident that the OTF of the system expressed by Eq. (9) is essentially the integral of the product of two first-kind Bessel functions. Since J_0 exhibits multiple zero-crossing oscillations with increasing frequency u , the integration result in Eq. (9) will also possess multiple zero-crossing oscillations as u increases, which is precisely the underlying reason why the MTF under vortex coding exhibits multiple zero-crossing oscillations. Moreover, this integral expression is closely related to the topological charge l : the larger the value of l , the more severe the oscillation of the zeroth-order Bessel function with spatial frequency u , thereby introducing more zeros into the MTF. The above analysis mathematically reveals the underlying reason why vortex encoding induces multiple zero-crossing oscillations in the MTF and why the number of zeros increases with l .

From the above discussion on the occurrence of multiple zero-crossing oscillations in the MTF of a vortex-encoded imaging system, it follows that when wavefront coding renders the system PSF radially symmetric (*i.e.*, independent of the polar angle), the inverse Fourier transform of the system's power spectrum will exhibit oscillatory multiple zeros. To further verify this conclusion, we take axicon encoding as an example and analyze its PSF and MTF. The wavefront phase of axicon encoding is $W(r, \theta) = \exp(iar/R)$, where a is the modulation coefficient, and R is the size of pupil radius. Substituting this phase into Eqs. (5) and (8) to calculate the PSF, the resulting PSF is shown in Fig. 4.

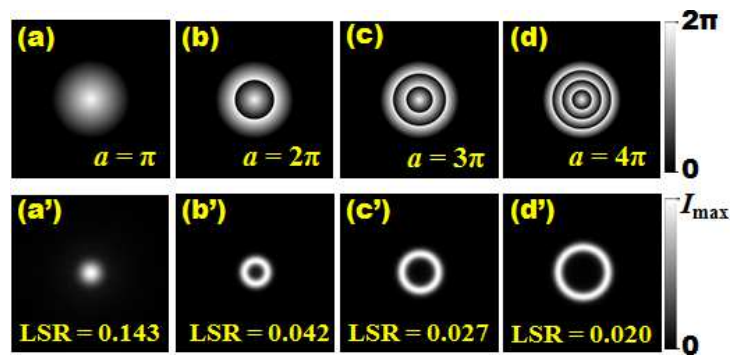


FIG. 3 Axicon encoding phase distribution maps and the corresponding PSF. The modulation coefficients for (a)–(d) are π , 2π , 3π , and 4π , respectively; (a')–(d') are the PSFs of the wavefront-coded imaging system under the corresponding modulation coefficients.

As shown by the PSF in Fig. 3, the power spectrum distribution of the axicon-encoded system, which corresponds to the PSF exhibits radial symmetry, *i.e.*, it is independent of the polar angle. Therefore, when performing the autocorrelation operation to obtain the OTF of the axicon-encoded system, Eq. (9) can still be applied. That is, in the inverse Fourier transform of the power spectrum, the

integral term contains a zeroth-order Bessel function with respect to the spatial frequency u , implying that its MTF will also exhibit oscillatory multiple zeros. The calculated MTF results are shown in Fig. 4, which is consistent with the conclusion that when the power spectrum is radially symmetric, the system MTF will present oscillatory multiple zeros. Similarly, the larger the modulation coefficient a , the more severe the oscillation of the zeroth-order Bessel function with increasing spatial frequency, thereby introducing more zeros into the MTF. This indicates that in wavefront coding systems, the occurrence of multiple zero-crossing oscillations in the MTF is not unique to vortex encoding. To avoid MTF zeros that would lead to loss of imaging detail information, the design of the coding phase should prevent the system's PSF from being radially symmetric.

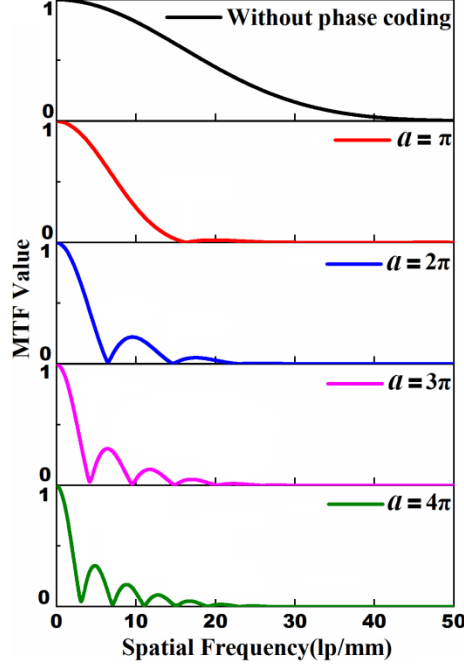


FIG.4 MTF distribution curves of a single-lens axicon-encoded imaging system under different a .

To prevent the PSF of the wavefront coding system from exhibiting multiple zero-crossing oscillations, we designed three nonlinear coding phases, denoted as $\exp(il\theta^2)$, $\exp(il\sin\theta)$, and $\exp(il\sin^2\theta)$. When the modulation coefficient $l = 3$, the calculated wavefront phases and their corresponding PSFs are shown in Fig. 6. It can be observed that under these three nonlinear wavefront coding phases, the PSFs of the system are not radially symmetric in any of the cases. Among them, coding $\exp(il\theta^2)$ yields a PSF with an approximately hollow distribution, and its LSR is smaller than the other two, indicating good laser suppression performance; whereas codings $\exp(il\sin\theta)$ and $\exp(il\sin^2\theta)$ produce PSFs that are not hollow, and their LSR values are larger, indicating poorer laser suppression performance.

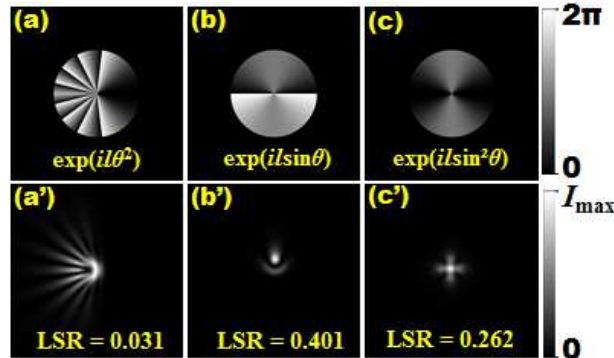


FIG. 5 Azimuthal nonlinear wavefront modulation phase distribution maps and the corresponding image-plane PSF. The wavefront coding function for (a)–(c) are $\exp(il\theta^2)$, $\exp(il\sin\theta)$, and $\exp(il\sin^2\theta)$, respectively; (a')–(c') are the corresponding PSFs. The value of the modulation coefficient l is 3.

Furthermore, we calculated the MTFs of the single-lens imaging system under the three nonlinear wavefront codings $\exp(il\theta^2)$, $\exp(il\sin\theta)$, and $\exp(il\sin^2\theta)$, with the modulation coefficient also set to 3; the results are shown in Fig. 6. Compared with vortex encoding, it can be seen that nonlinear encoding of the polar angle makes the PSF non-radially symmetric, and in this case, the system MTF does not exhibit multiple oscillatory zeros. However, when comparing the four wavefront codings including vortex encoding, it is found that although coding $\exp(il\theta^2)$ outperforms vortex encoding in terms of LSR and avoids oscillatory zeros in the MTF, its MTF distribution in the spatial frequency domain is even narrower than that of vortex encoding. On the other hand, although codings $\exp(il\sin\theta)$ and $\exp(il\sin^2\theta)$ can provide better MTF distribution characteristics than vortex encoding, their LSRs are much larger than that of vortex encoding. Therefore, simply pursuing non-radial symmetry of the PSF is not a principle to be followed in coding-phase design, because this approach cannot achieve a good balance between laser suppression performance and the preservation of more imaging details.

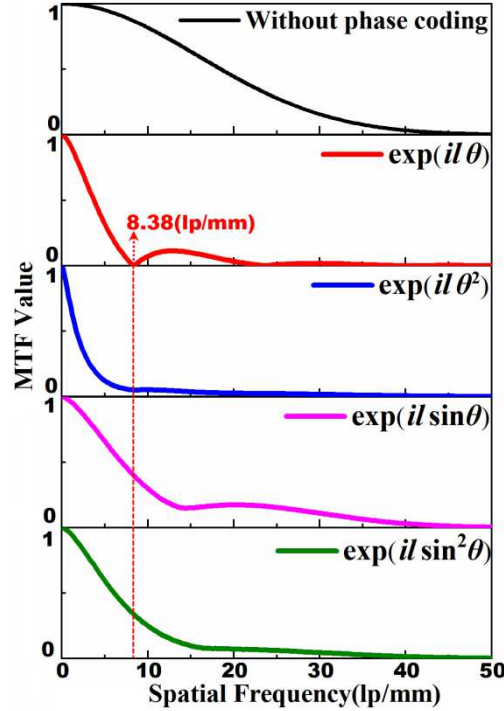


FIG. 6 MTFs of different wavefront coding systems, and the values of the modulation coefficient are $l = 3$.

The above MTF calculations for nonlinear polar-angle phase coding indicate that the imaging systems corresponding to wavefront codings $\exp(il\sin\theta)$ and $\exp(il\sin^2\theta)$ have relatively broad MTFs in the spatial frequency domain, and their redistribution of optical energy on the image plane only considers expansion along the image-plane direction. To improve the laser suppression performance of these two coding schemes, we further introduce spherical aberration to disperse the optical energy along the optical axis as well. After introducing spherical aberration, the phase functions of the wavefront coding become composite functions $\exp(il\sin\theta + i\beta r^4)$ and $\exp(il\sin^2\theta + i\beta r^4)$. We calculated their wavefront phases and the PSFs on the image plane, still with the modulation coefficient $l = 3$, and the results are shown in Fig. 7. It can be seen from Fig. 7 that after introducing spherical aberration, the PSFs of the system under

composite coding are not only further expanded but also exhibit significant changes in their morphology.

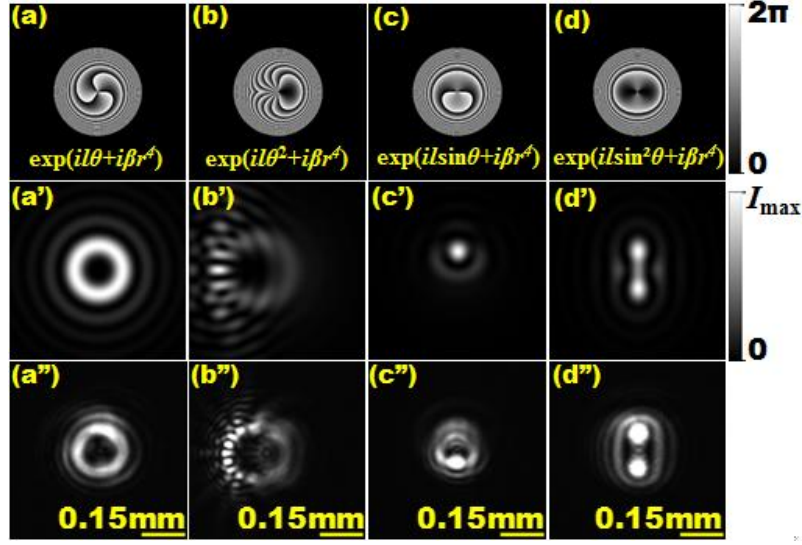


FIG. 7 Phase distribution maps and the corresponding PSF of composite encodings. The wavefront coding function for (a)–(d) are $\exp(il\theta + i\beta r^4)$, $\exp(il\theta^2 + i\beta r^4)$, $\exp(il\sin\theta + i\beta r^4)$, and $\exp(il\sin^2\theta + i\beta r^4)$, respectively; (a')–(d') are the corresponding PSFs; (a'')–(d'') are the corresponding intensity distribution of the image plane collected by the CCD. The values of the modulation coefficient are $l = 3$, and $\beta = 20\pi$.

To verify the reshaping effect of composite coding on the PSF, we loaded the coding phase onto a spatial light modulator (SLM) and placed it at the pupil plane of the single-lens imaging system. The experimental optical setup is shown in Fig. 8, and the PSFs on the image plane captured by the CCD are presented in Fig. 7(a'')–(d''). Comparing Fig. 7(a')–(d') with (a'')–(d''), it can be seen that the system PSFs calculated from the Fourier transform of the pupil function are in good agreement with the experimental results, indicating that after loading the composite coding function onto the pupil plane of the system, the coding phase can effectively reshape the PSF.

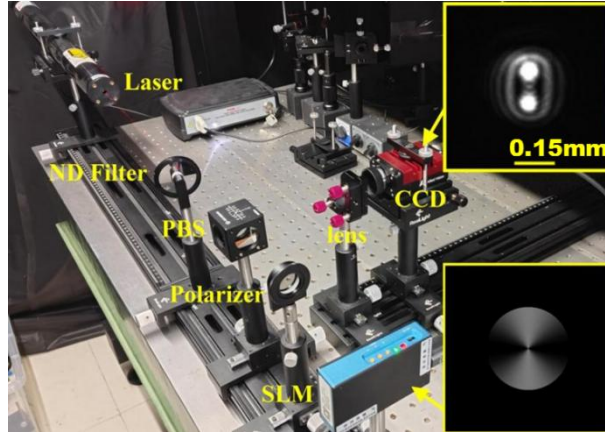


FIG. 8 Experimental optical setup for single-lens wavefront-coded imaging. Laser:632nm,JDSU 1145P;SLM:FSLM-2K39-P02;CCD:GT1920.

Obviously, the composite coding scheme further expands the point spread function of the imaging system, meaning that the energy on the image plane is further dispersed. However, to determine whether this composite coding scheme can improve laser suppression performance while preserving more imaging details, it is necessary to further calculate the system MTF. We calculated the LSR and MTF for

the four composite coding systems shown in Fig. 7(a)–(d), and the results are presented in Fig. 9. It can be found that the introduction of aberration-coding phase effectively enhances the laser suppression effect, but at the same time, it significantly degrades the system MTF. Comparing coding schemes $\exp(il\theta + i\beta r^4)$ and $\exp(il\sin^2\theta + i\beta r^4)$, it is evident that although coding $\exp(il\sin^2\theta + i\beta r^4)$ avoids multiple zero-crossing oscillations in the MTF and maintains a better MTF distribution, its laser suppression performance is far inferior to that of coding $\exp(il\theta + i\beta r^4)$. Further comparison of the laser suppression ratio and MTF between coding $\exp(il\sin^2\theta + i\beta r^4)$ and coding $\exp(il\theta)$ in Fig. 9 and Fig. 2 reveals that composite coding scheme $\exp(il\sin^2\theta + i\beta r^4)$ (*i.e.*, simultaneous diffusion of light intensity along both the image plane and the optical axis) fails to achieve a balance between laser suppression and the preservation of more imaging details.

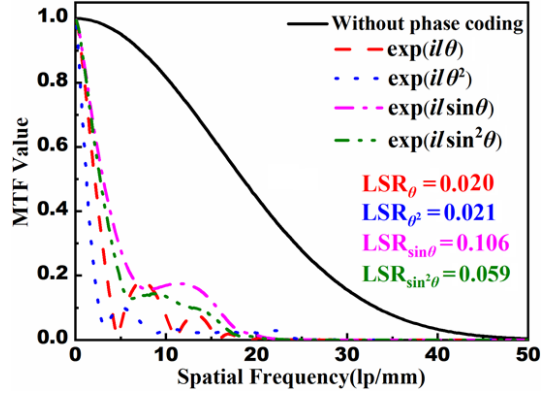


FIG. 9 MTFs of different composite encodings systems, and the values of the modulation coefficient are $l = 3$, and $\beta = 20\pi$.

III. LSR and MTF of the VE-PACE wavefront coded imaging systems

After comparing the LSRs of the coding phases $\exp(il\theta)$, $\exp(il\theta^2)$, $\exp(il\sin\theta)$, $\exp(il\sin^2\theta)$, and $\exp(iar/R)$, we found that if the PSF exhibits a hollow annular distribution, the wavefront coding achieves better laser suppression performance (*i.e.*, a smaller LSR). However, if the PSF is radially symmetric, the system MTF again exhibits multiple zero-crossing oscillations. Considering both of these scenarios, a natural question arises: if the wavefront coding produces a PSF that is non-radially symmetric and hollow annular, can the system simultaneously achieve good laser suppression and good imaging performance? To this end, we adopt a composite coding strategy that combines vortex encoding with polar-angle cubic encoding (VE-PACE), aiming to construct a non-radially symmetric hollow annular PSF, and we investigate whether composite coding VE-PACE can effectively balance the trade-off between laser suppression performance and the preservation of more imaging details.

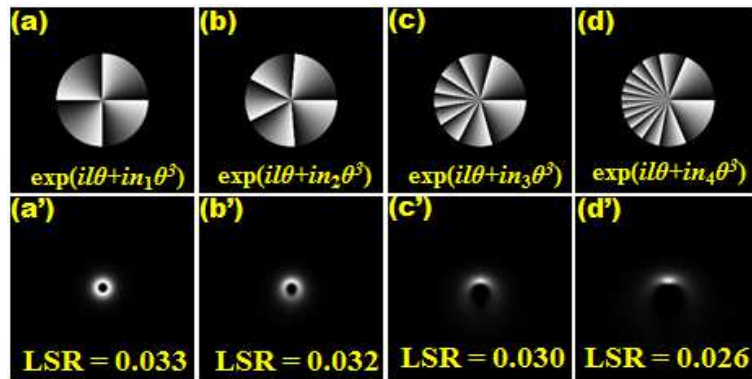


FIG. 10 Wavefront phase and PSF distributions of the composite-coded VE-PACE imaging system under different modulation coefficients: (a) $l = 4$, $n = 0$; (b) $l = 4$, $n = 0.1$; (c) $l = 4$, $n = 0.5$; (d) $l = 4$, $n = 1$.

As shown in Fig. 10, the introduction of nonlinear phase $\exp(in\theta^3)$ gradually transforms the PSF of the system under vortex encoding from an annular radially symmetric distribution to a hollow asymmetric distribution. Comparing the LSRs under different modulation coefficients, it can be seen that as the modulation coefficient n increases, the LSR further decreases. Further calculating the MTF of the system under the composite modulation function $\exp(il\theta + in\theta^3)$, when the topological charge $l = 4$ and the modulation coefficient n takes the values 0, 0.1, 0.5 and 1 respectively, the distribution curves of the system's MTF in the spatial frequency domain are shown in Figure 11. The results indicate that by introducing a nonlinear coding phase $\exp(in\theta^3)$, the PSF of the system becomes an asymmetric annular hollow distribution, and its MTF avoids multiple zero-crossing oscillations. Comparing different values of the modulation coefficient n reveals that when $n = 0.1$, the composite coding $\exp(il\theta + in\theta^3)$ yields the best MTF performance for the system, which is even superior to that of pure vortex coding, and its laser suppression effect is also better than that of pure vortex coding. Analyzing the four point spread function distribution diagrams in Figure 10 further shows that, by aiming to construct a non-radially symmetric hollow PSF as the coding target, it is possible to effectively balance the laser suppression capability and detail imaging performance of the wavefront coding system.

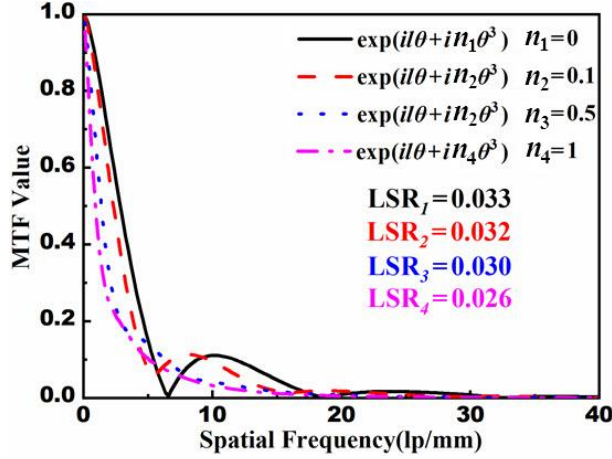


FIG. 11 Distribution curves of the MTF in the spatial frequency domain for the VE-PACE coding system under different modulation coefficients, along with the corresponding LSR of the coding system.

As shown in Fig. 11, after introducing coding phase $\exp(in\theta^3)$, the MTF distribution curve of the VE-PACE system avoids the zero-crossing oscillations compared to the simple vortex coding system, which implies that the system should retain more details during imaging and reduce irreversible information loss caused by coding. However, it should also be noted that at some spatial frequencies, the MTF value corresponding to VE-PACE is lower than that of vortex coding. To verify the imaging characteristics of these two coding methods, we used a portrait of Newton as the target image and performed encoding and decoding using composite coding VE-PACE and vortex coding respectively: first, the image was convolved with the PSF corresponding to the respective coding, followed by Wiener filter decoding, with the results shown in Fig. 12. By comparing with the original image and calculating the Structural Similarity Index (SSIM), it can be seen that the decoding performance of composite coding VE-PACE is superior to that of vortex coding. This result confirms that, after introducing the nonlinear phase $\exp(in\theta^3)$ (*i.e.*, constructing a non-radially symmetric hollow PSF), the wavefront coding system can not only improve laser suppression performance but also better preserve imaging details.

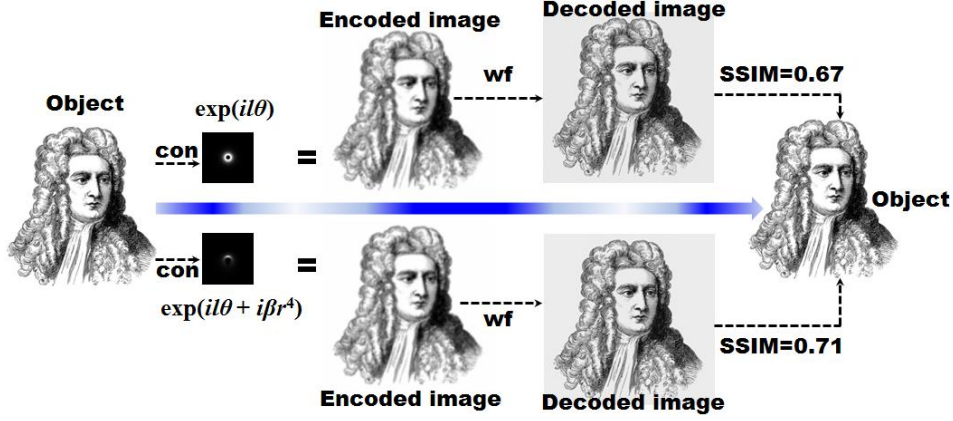


FIG. 12 Simulated encoding and decoding of information for the imaging system under VE-PACE and vortex encoding. The modulation coefficient are $l = 4$, and $n = 0.1$.

IV. Separated apochromatic imaging system with VE-PACE

To verify the feasibility of VE-PACE $\exp(il\theta + in\theta^3)$ in imaging systems, we take a separated apochromatic imaging system as an example and conduct corresponding design and verification studies. Specifically, after establishing the system in ZEMAX software, we introduce the above coding phase at the pupil plane (as shown in Fig. 13) to achieve effective modulation of the incident optical information. From the spot diagram of the right-side system in Fig. 13, it can be seen that under the modulation of the compound coding phase, the shape of the spot diagram of the separated apochromatic imaging system has clearly deviated from the distribution of the Airy disk of an ideal imaging system.

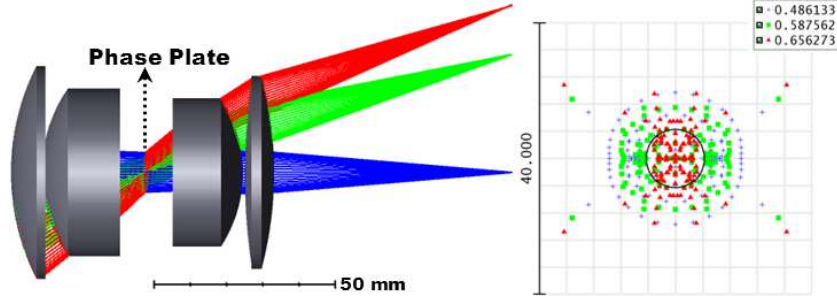


FIG. 13 Schematic diagram and spot diagrams of the separated achromatic imaging system under VE-PACE encoding. The modulation coefficient are $l = 4$, and $n = 0.1$.

After completing the modeling design of the VE-PACE separated apochromatic imaging system, we further analyze its MTF using ZEMAX software. Fig. 14 presents the MTF curves for the system without wavefront coding, the vortex-coding system, and the VE-PACE system (with modulation coefficient $l = 4$ and $n = 0.1$). The inset in Fig. 14 shows the wavefront phase distribution of the VE-PACE. As seen from the figure, after wavefront coding, the system MTF exhibits a significant decrease with increasing spatial frequency in the low-frequency region. Comparing the two coding schemes, the MTF performance of the VE-PACE system is clearly superior to that of the vortex-coding system. Within the spatial frequency range below 100 lp/mm, the MTF values of the VE-PACE system are all greater than 0.2. When the pixel size of the image sensor is $5 \mu\text{m}$, its resolution limit is $10 \mu\text{m}$, which corresponds exactly to a spatial frequency of 100 lp/mm. Therefore, taking 100 lp/mm as the resolution limit of the imaging system, the imaging system with this VE-PACE essentially does not lose background information. Furthermore, when $l = 4$ and $n = 0.1$, the LSR of this compound coding reaches 0.032, which

means that the system can reduce the peak laser power on the imaging sensor to less than 1/31 of its original value, thus effectively providing laser protection. Further comparison of the MTF curves of vortex coding and VE-PACE reveals that, in the phase design of wavefront coding, constructing a non-radially symmetric hollow PSF distribution is an effective strategy to balance the trade-off between laser suppression performance and the preservation of more imaging details. The coding phase designed according to this rule can achieve better laser suppression performance while maintaining more imaging details.

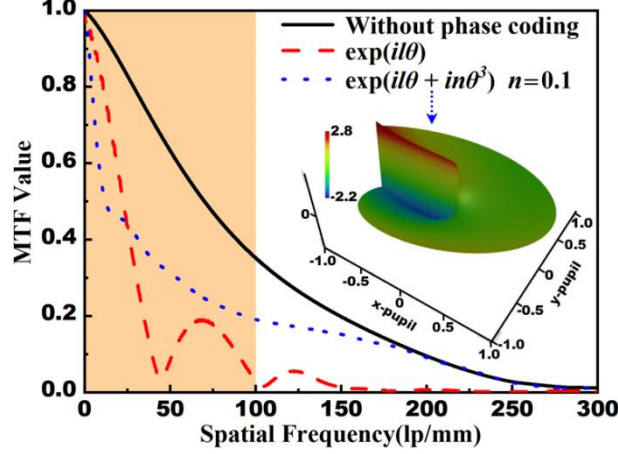


FIG. 14 MTF curves in the spatial frequency domain for the separated achromatic imaging system under VE-PACE and vortex encoding. The modulation coefficient are $l = 4$, and $n = 0.1$.

V. Conclusion

How to balance the LSR and the preservation of imaging details is a core issue in wavefront coding design. By calculating the MTF of a vortex-coding imaging system and analyzing the physical mechanism behind its multiple zero-crossing oscillations in the MTF, we find that constructing a non-radially symmetric PSF can effectively avoid such oscillations. Further comparison of the PSFs and LSRs of various nonlinear wavefront coding phases reveals that constructing hollow PSF can achieve better laser suppression performance. Therefore, in wavefront coding phase design, targeting a non-radially symmetric hollow PSF can provide better laser protection while retaining more imaging details. Specifically, using the coding phase VE-PACE corresponding to this target as the wavefront coding for laser protection in a separated achromatic imaging system can reduce the peak power at the image plane by a factor of 31, while ensuring that the MTF values of systems with spatial frequencies below 100 lp/mm are all greater than 0.2. The results presented in this paper can serve as a valuable reference target for the design of coding phases.

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Disclosures

Conflict of interest The authors declare no conflict of interest.

References

- [1] Y. Liu, W. Sun, J. Zhang, A. Liu, Z. Dai, H. Luo, J. Bian, Y. W and Q. Ye, Enhancing infrared imaging robustness against laser-induced damage: a wavefront coding and Mamba-UNET approach, *Opt. Express*. **34**(8), 14233-14248 (2026).
- [2] S. Ravichandran, M. Huault, R. Lera, C. Z. He, A. Longman, R. Fedosejevs, R. Luis and W. T. Hill III, Imaging electron angular distributions to assess a full-power petawatt-class laser focus. *Phy. Rev. A*, **108**(5), 053101 (2023).
- [3] A.K. Varshney, G. Singhal and J. Nayak, High power lasers for directed energy applications: Developments and challenges, *Infrared Phys. Technol.* **136**, 105064 (2024).
- [4] A. Schweinsberg, J. Kuper and R.W. Boyd, Loss of spatial coherence and limiting of focal plane intensity by small-scale laser-beam filamentation. *Phy. Rev. A—Atomic, Molecular, and Optical Physics*, **84**(5), 053837 (2011).
- [5] Q. Ye, Y. Wu, H. Zhang, Y. Li, L. Wang and K. Sun, Experimental damage thresholds of a laser suppression imaging system using a cubic phase plate, *Chin. Opt. Lett.* **21**(4), 041403 (2023).
- [6] J. R. Solin, Hardening a notional missile warning satellite telescope against jamming and damage by ground, airborne, and space-based lasers, *Proc. SPIE*. **11422**, 219-229 (2020).
- [7] W. Liu, Z. Yan, H. Liu, Y. Meng and Z. Xie, Research Progress on Two-Dimensional Nonlinear Optical Limiting Laser Protection Materials and Devices, *Chin. J. Lasers*. **53**(7), (2026).
- [8] Y. Zhang, M. Chen, H. Wang, X. Zhou and J. Yu, Laser Ablation Behavior and Development Trend of Ceramic Matrix Composites, *Bull. Chin. Ceram. Soc.* **45**(5), 1727 (2026).
- [9] S. Jin, N. Dong, Z. Yan, J. Ji, W. Yu, J. He and J. Wang, Microstructure modulation and mid-infrared optical properties of VO_x films, *Infrared Laser Eng.* **55**(1), 20250468-1-20250468-10 (2026).
- [10] Y. Li, Q. Ye, Y. Wu, K. Sun, H. Zhang and X. Sun, Research progress of laser protection technology for optoelectronic imaging system, *Infrared Laser Eng.* **52**(6), 20230192-1-20230192-15 (2023).
- [11] Jr. Dowski and W.T. Cathey, "Extended depth of field through wave-front coding," *Appl. Opt.* **34**(11), 1859-1866 (1995).
- [12] Y. Liu, B. Chen, E. Li, J. Wang, A. Marcelli, S.W. Wilkins, H. Ming, Y. Tian, K.A. Nugent, P. Zhu and Z. Wu, Phase retrieval in x-ray imaging based on using structured illumination. *Phy. Rev. A*, **78**(2), 023817 (2008).
- [13] G.J. Ruane, A.T. Watnik and G.A. Swartzlander, Reducing the risk of laser damage in a focal plane array using linear pupil-plane phase elements. *Appl. Opt.* **54**(2), 210-218, (2015).

- [14] A.T. Watnik, G.J. Ruane and G.A. Swartzlander, Incoherent imaging in the presence of unwanted laser radiation: vortex and axicon wavefront coding, *Opt. Eng.* **55**(12),123102-123102(2016).
- [15] J. H. Wirth, A.T. Watnik and G.A. Swartzlander, PSF Engineering for Sensor Protection, in *Frontiers in Optics 2017* (Optica Publishing Group, 2017), paper JTu2A.95.
- [16] J. H. Wirth , A.T. Watnik and G.A. Swartzlander, Experimental observations of a laser suppression imaging system using pupil-plane phase elements, *Appl. Opt.* **56**(33),9205-9211(2017) .
- [17] L. Wang, Q. Ye, J. Nie and X. Sun, Optimized asymmetrical arcsine phase mask for extending the depth of field, *IEEE Photonics Technol. Lett.* **30**(14),1309-1312(2018).
- [18] L. Wang, X. Dou, Q. Ye, J. Nie and X. Sun, Wavefront coded light-field imaging system to achieve substantial retroreflection reduction and anti-laser blinding property, *Optik.* **192**,162947(2019).
- [19] Y. Li, Q. Ye, Y. Wu, H. Zhang, H. Luo, K. Sun and X. Sun, Experimental validation and mathematical simulation for laser protection performance of light field imaging, ”*Appl. Opt.* **62**(36),9621-9630(2023).
- [20] H. Luo, Y. Li, J. Zhang, H. Zhang, Y. Wu and Q. Ye, Performance analysis of spiral axicon wavefront coding imaging system for laser protection, *Curr. Opt.* **8**(4),355-365(2024).
- [21] X. Peng, H. Gemar, E. Fleet, K. Novak, A.T. Watnik and G. Swartzlander, Learning to See Through Flare,”in *Proceedings of the IEEE/CVF International Conference on Computer Vision(IEEE, 2025)*, paper.7410-7421.
- [22] S. Zhou, D. Wang, H. Ren, S.Li, Z. Li and S. Chen, Sinusoidal phase mask for balancing laser suppression and image quality in a wavefront coding imaging system.”*Opt. Express.* **34**(8),15754-15766(2026).